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EFFECT OF RADIAL LOAD DISTRIBUTION ON THE FIRST HARMONIC

INFLOW VELOCITY OF A HELICOPTER ROTOR

AT TRANSITION SPEEDS

by

Harvey R. Chaplin

AND SURFACE EFFECTS DEPARTMENT

DTNSRDC/ASED-84/03

April 1984

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A joint Navy/NASA experimental investigation was conducted in October 1983 in the Langley Research Center VSTOL Wind Tunnel to test the hypothesis that helicopters with unusually hub-weighted radial load distributions should experience a more severe first harmonic inflow velocity field during transition than ordinary helicopters. This report presents an approximate analysis of the experimental results. The hypothesis is strongly supported. Compared to the rotor configuration with the most tip-weighted load
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distribution, the configuration with the most hub-weighted distribution appears to have experienced an approximately 50 percent greater first-harmonic inflow at a 50 percent greater critical flight speed.

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NOTATION

$B0$	Mean blade root duct pressure, psig
$B1$	Amplitude of first-harmonic blade root duct pressure, psi
C_T	Thrust coefficient, $T/(\pi \rho R^2 V_{tip}^2)$
$K_{\ell am}$	Nondimensional correlation parameter, $\lambda_1^*/\lambda_1^{\ddagger}$
M_f	Amplitude of first-harmonic blade root flapping moment, ft-lb
M_{fc}	$M_f \cos (\psi_f)$
R	Rotor radius, ft
r	Radial coordinate from hub center, ft
T	Thrust, lb
V_k	Free-stream velocity, knots
V_o	Free-stream velocity, ft/sec
V_{tip}	Tip speed, ft/sec
w	Inflow velocity normal to disk, ft/sec
α_s	Shaft angle, deg
Θ	Collective blade angle, deg
λ	Inflow ratio, w/V_{tip}
λ_o	Mean value of λ
λ_1	First-harmonic cosine component of λ
μ	Advance ratio, V_o/V_{tip}
μ^*	Normalized value of μ, $\mu/\sqrt{C_T/2}$
λ_o^*	Normalized value of λ_o, $\lambda_o/\sqrt{C_T/2}$
λ_1^*	Normalized value of λ_1, $\lambda_1/\sqrt{C_T/2}$

$\lambda_o^{\ddagger}$ Value of λ_o^{*} predicted by Reference 1

$\lambda_1^{\ddagger}$ Value of λ_1^{*} predicted by Reference 1

ρ Ambient air density, slugs/ft^3

ψ_f Azimuthal phase angle of M_f, deg

ψ_p Azimuthal phase angle of B1, deg

ABSTRACT

A joint Navy/NASA experimental investigation was conducted in October 1983 in the Langley Research Center VSTOL Wind Tunnel to test the hypothesis that helicopters with unusually hub-weighted radial load distributions should experience a more severe first-harmonic inflow velocity field during transition than ordinary helicopters. This report presents an approximate analysis of the experimental results. The hypothesis is strongly supported. Compared to the rotor configuration with the most tip-weighted load distribution, the configuration with the most hub-weighted distribution appears to have experienced an approximately 50 percent greater first-harmonic inflow at a 50 percent greater critical flight speed.

ADMINISTRATIVE INFORMATION

INTRODUCTION

In late 1979, flight tests were undertaken by Kaman Aerospace Corporation on an H-2 helicopter equipped with an experimental circulation control rotor (XH-2/CCR). It was found to be much more difficult to trim the helicopter in pitch at low speeds than anticipated; in fact, the flight tests were eventually abandoned with no flights at speeds exceeding the critical transition speed.

Although a number of problems were found which could qualitatively explain the pitch trim difficulty, it was hypothesized that, because the radial load distribution on a circulation control rotor is much more hub-centered than that on an ordinary rotor, the transition inflow field at critical speed might be more severe. Although analyses of the flights completed did not indicate unusual inflow characteristics, the possibility remained that unusual effects, including a higher-than-normal critical transition speed, might have shown up had further flights at higher speeds been possible.

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In 1983, an agreement was reached between the David Taylor Naval Ship Research and Development Center (DTNSRDC) and the National Aeronautics and Space Administration to conduct experiments in the Langley Research Center (LRC) VSTOL Wind Tunnel to seek evidence concerning possible effects of radial load distribution on the transition inflow field. These experiments were completed in October 1983 by a joint LRC/DTNSRDC team using an existing DTNSRDC circulation control rotor model. This report presents an approximate analysis of the results.

EXPERIMENTS

The rotor model was 80-in. in diameter with four, 5-in.-chord blades. These blades were judged small enough to yield reasonably valid transition data in the LRC VSTOL Wind Tunnel (Figure 1). The model was equipped with a pneumatic valve system capable of providing blade duct mean pressures up to 10 psig and azimuthal 1-per-rev harmonic variation of the pressure of amplitude up to about 60 percent of the mean. The valve characteristic was such that a 2-per-rev harmonic variation one-third the amplitude of the 1-per-rev component and 90 deg out of phase with it also resulted. The model was equipped with blade duct pressure transducers, blade root flapping moment strain gages, and azimuth reference signal generators. A more complete description of the model is given in Reference 1.

The model was mounted on a four-component DTNSRDC load cell balance designed to measure thrust, pitching moment, rolling moment, and yawing moment during hover tests. All tests were performed at a tip speed of 500 ft/sec. The thrust reading of this balance was also to be used for the forward flight tests. Unfortunately, the balance system malfunctioned during early hover tests. Enough data, however, were acquired before the malfunction to confirm that the model was functioning properly and to establish an approximate correlation between the first-harmonic flapping moment strain gage measurements and the actual root (hub-center) flapping moment. All analyses of the transition data then had to be performed in terms of root flapping moment.

A tabulation of the experimental results for the transition inflow analyses is presented in Table 1. In addition to the tabulated data, a number of other data channels were recorded including the azimuth angle of the maximum opening

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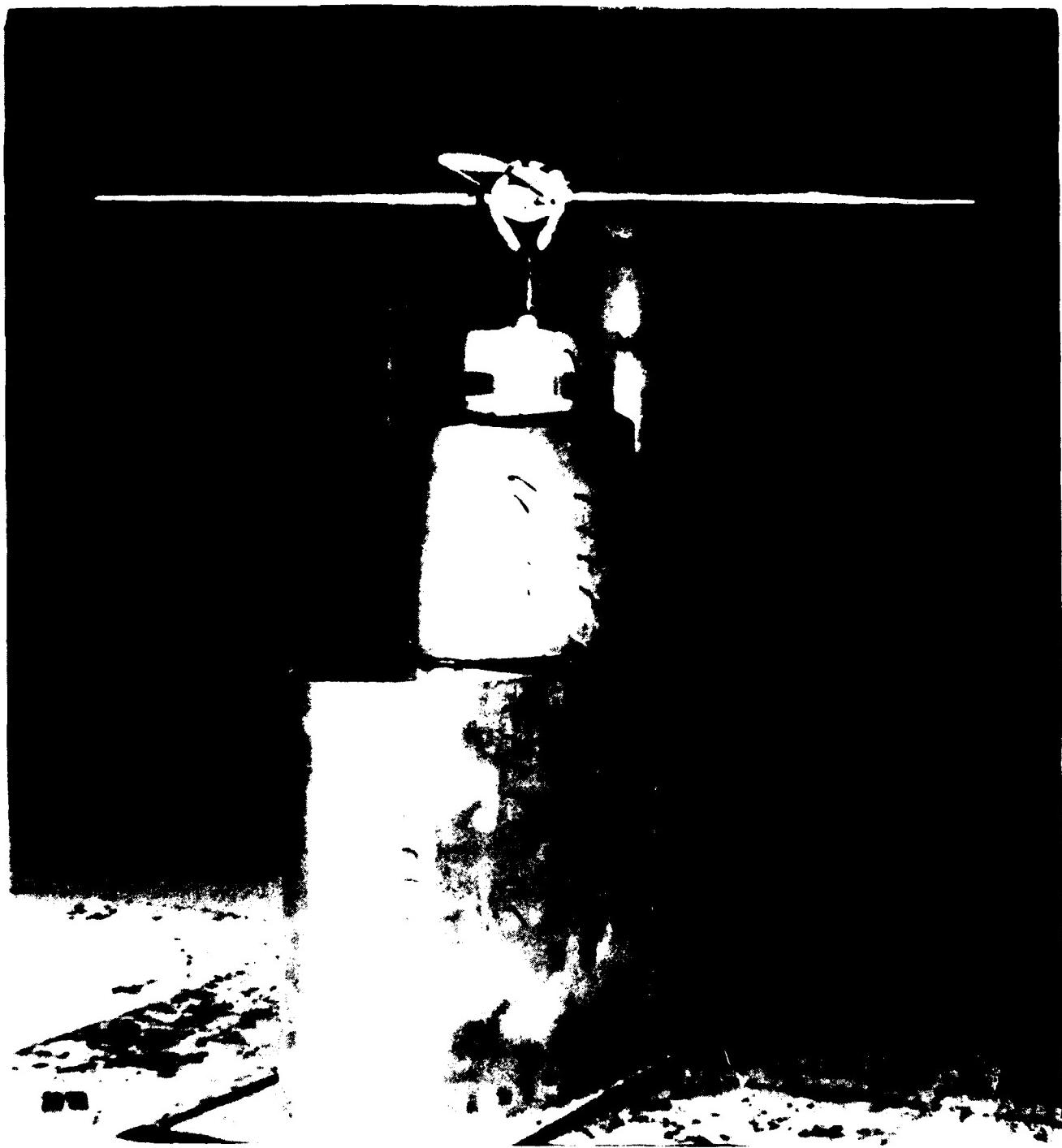
Figure 1 - Rotor Model in Langley Research Center
4- by 7-Meter Wind Tunnel

of the pneumatic valve (which was of the eccentric-circular-cam type) and the output of blade duct pressure transducers located at the tip and a mid-radius position, in addition to the "blade root" (10 percent-radius) transducer output used in the analysis. Comparison of the first-harmonic phase angles of these various quantities with each other and with the recorded cam angle reveals random inconsistencies in the phase angles on the order of ±10 deg. Since LRC was unable to provide on-site reduction of the high-speed data, the unusually large error band was not detected in time to initiate efforts to identify and correct the cause.

In addition to the random inconsistencies, there are also regular inconsistencies—notably that the recorded phase angle (i.e., azimuthal position of first-harmonic peak) of the duct pressure at the blade tip lags that at the root by about 3 deg on average; whereas, due to the time lag involved in near-sonic transport of a pressure signal from root to tip, the blade root first-harmonic pressure peak should lead that at the tip by about 23 deg. The results of the analyses suggest that the recorded tip pressure phase is more nearly correct.

AERODYNAMICS PERFORMANCE CODE

The performance code used in the analyses is an undocumented code developed by the author on an HP-9836 desk computer for quick-look investigations of the effects of various design parameters on the performance of circulation control and X-Wing rotors. The code employs a curve-fit approximation to the experimentally determined two-dimensional characteristics of the circulation control airfoils used on this model rotor, including Reynolds number and compressibility effects. It also employs a "distributed momentum" variation of the approximate inflow equations presented by Blake and White.[2] The Blake and White formulation can be written as:

$$\lambda = [\lambda_0^{\ddagger} + \lambda_1^{\ddagger} \ r/R \ \cos(\psi)] \ \sqrt{C_T/2} \tag{1}$$

where

$$\lambda_0^\ddagger = \sqrt{(\sqrt{4+\mu^{*4}} - \mu^{*2})/2} \qquad (2)$$

$$\lambda_1^\ddagger = \sqrt{8}\ \mu^*/(\sqrt{4+\mu^{*4}} + \mu^{*2}) \qquad (3)$$

The "distributed momentum" variation merely replaces the quantity $\lambda_0^\ddagger$ by the quantity $\lambda_0^\ddagger \sqrt{(\text{local disk loading})/(\text{average disk loading})}$.

In the present investigation, a further modification was introduced. The quantity $\lambda_1^\ddagger$ was replaced by the quantity $K_{\ell am} \lambda_1^\ddagger$ so that the first-harmonic inflow term could be easily varied iteratively (by varying $K_{\ell am}$) to determine what value of this term was needed for best correlation with the experimental results. For purposes of this investigation, the "rigid rotor" option of the code was used; that is, elastic deflections of the blade were neglected.

It was intended to validate the aerodynamics performance code (and, if needed, make empirical adjustments to it) by comparing calculated to measured thrust and hub moments in hover at three blade angles and several combinations of blade duct mean and cyclic pressure. As previously mentioned, only one collective angle was completed before the thrust balance malfunctioned, and only a few cyclic pressures at that collective angle were completed before the hub moment balance began to behave erratically.

Correlation of the few valid thrust data points with previous measurements (unpublished) and with the calculated behavior is shown in Figure 2. It is concluded that (1) the model was functioning properly, and (2) the thrust predictions from the aerodynamics performance code are satisfactory.

The few valid hub moment measurements were used to establish the approximate relationship:

$$\text{Mean Hub Moment} \doteq 2.5\ M_{fe}$$
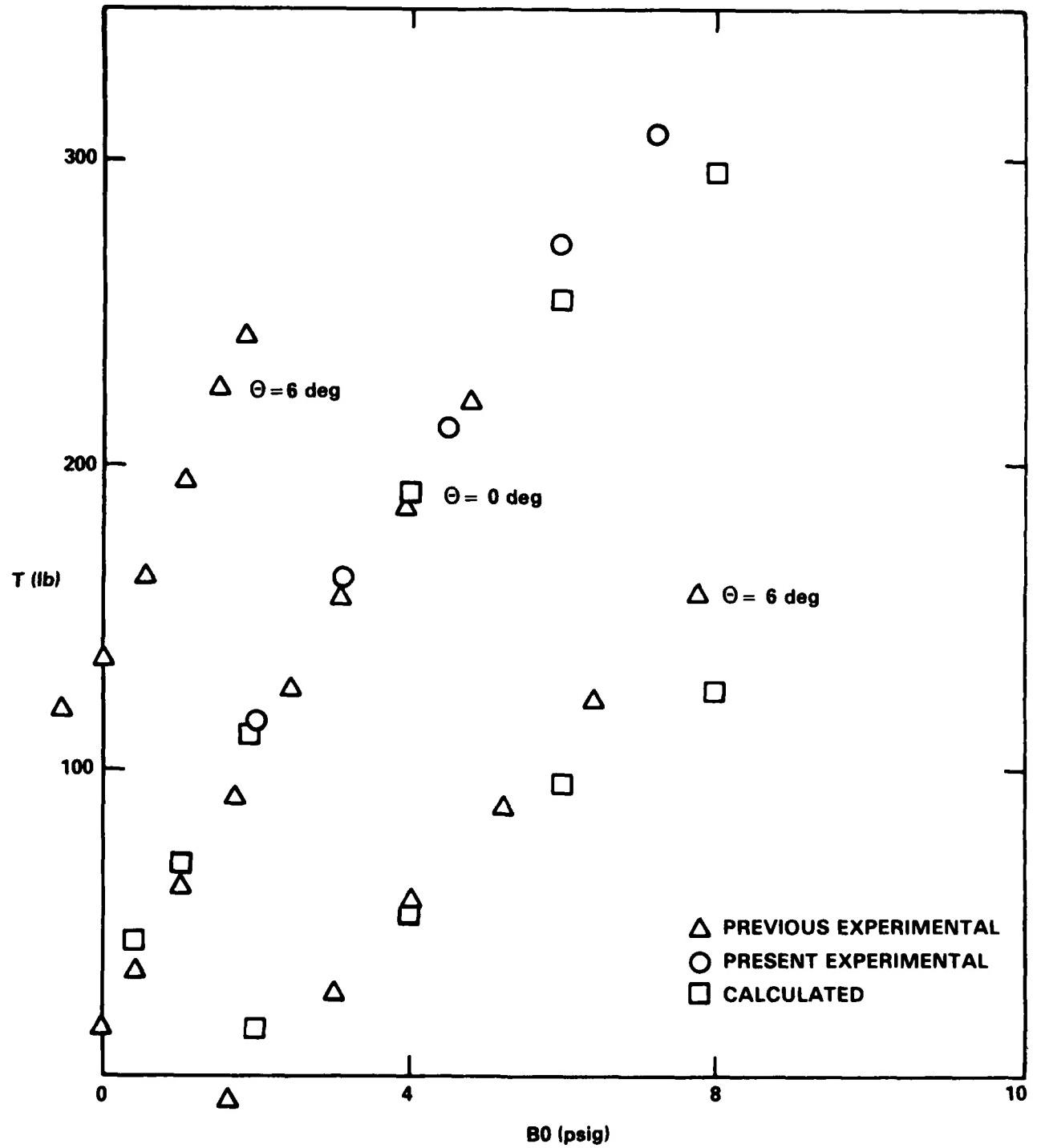
Figure 2 – Comparison of Measured and Calculated Thrust
$(V_k = 0, V_{tip} = 500 \text{ fps})$

where M_{fe} is the first-harmonic amplitude of measured flapping moment (measured by a strain gage bridge at the 12-percent radius station). From this it is deduced that:

$$M_f \doteq 1.25 \ M_{fe}$$

where M_f is the root (hub center) flapping moment. This relationship was employed in all subsequent analyses.

Correlation of the measured flapping moments with calculated behavior is shown in Figure 3. The flapping moment predictions from the aerodynamics performance code are also satisfactory. Consequently, empirical adjustments to the code were not needed.

ANALYTICAL PROCEDURE

No inflow quantities were directly measured in the experiment. The plan was to determine for each *experimental data* point the value of

$$\lambda_1^* = K_{\ell am} \ \lambda_1^{\ddagger}$$

which, when substituted for $\lambda_1^{\ddagger}$ in Equation (1), would yield agreement between the measured and calculated first-harmonic root flapping moment amplitude and phase (M_f, ψ_f). The calculation would have employed the measured values of root pressure zeroth, first- and second-harmonic amplitude and first- and second-harmonic phase.

In view of the random and systematic irregularities in the pressure phase measurements, this plan was modified slightly:

1. It was assumed that the best first estimate of actual effective root pressure phase was a value leading the measured phase by 20 deg.

2. From this estimate, random variations on the order of ±10 deg can be expected.

3. To reduce the time required for analysis, it was decided to define "agreement" by:

Figure 3 – Comparison of Measured and Calculated Hub Moments
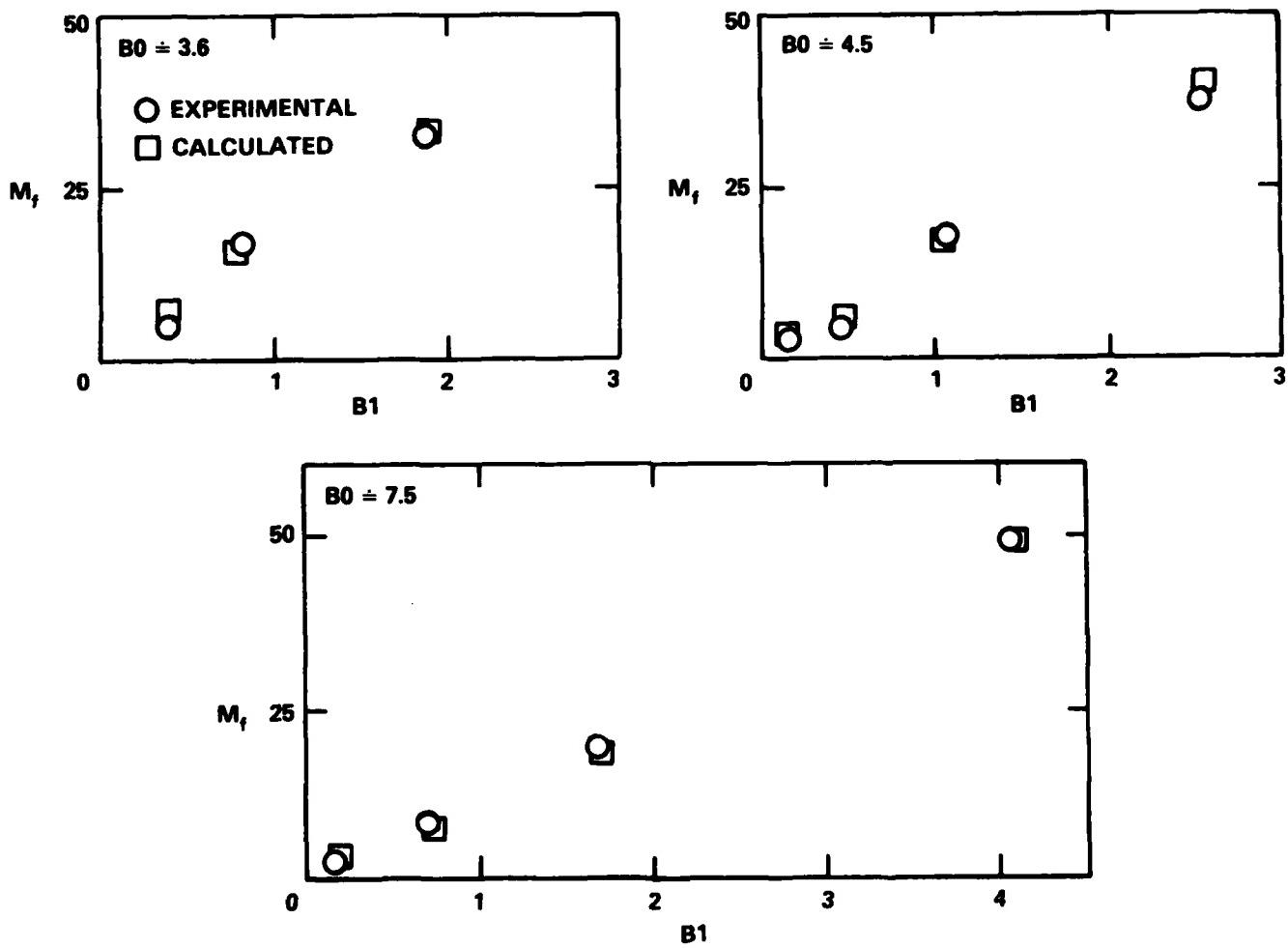

Figure 3a – θ = -3 Degrees

Figure 3 (Continued)

Figure 3b — θ = 0 Degrees

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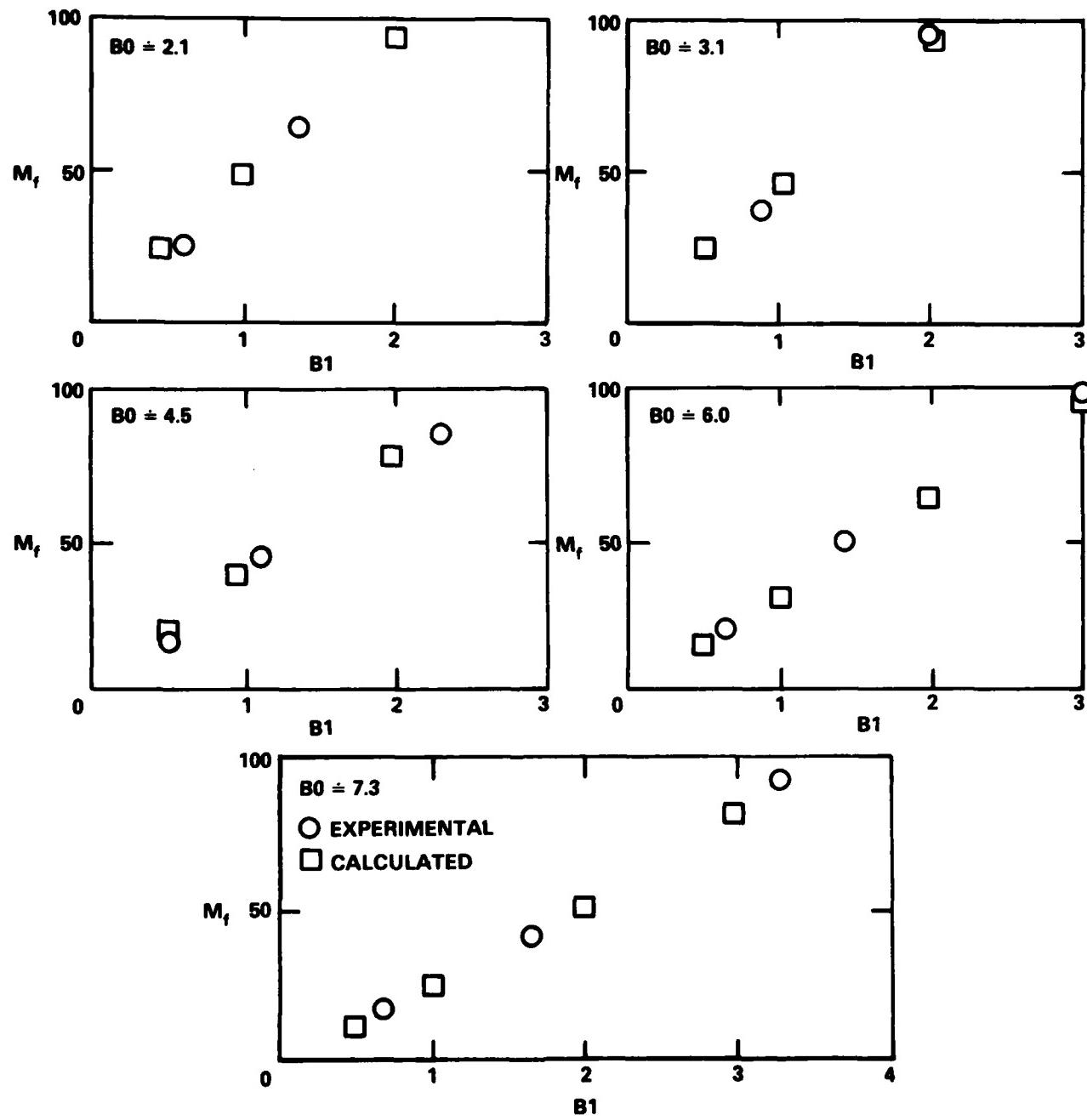
a. Measured $M_f \cos \psi_f$ = Calculated $M_f \cos \psi_f$.

b. Discrepancies between measured ψ_p and calculated input ψ_p should both be "reasonable" in light of the above-discussed data irregularities.

These regrettably soft criteria may become more understandable in light of the example presented in Figure 4. Here the experimental results for Run 61/Test Point 1 are shown with the calculated results for various combinations of input pressure phase, ψ_p, and input inflow correlation parameter, $K_{\ell am}$. Note that the "reasonable" range of input ψ_p (+1 deg – 20 ±10 deg = -9 to -29 deg) brackets the input ψ_p of -12 deg required to produce agreement in both $M_f \cos \psi_f$ and $M_f \sin \psi_f$. More importantly, note that the value of $K_{\ell am}$ required to produce agreement in $M_f \cos \psi_f$ alone is rather insensitive to small errors in either ψ_f or ψ_p. This insensitivity to errors in ψ_p prevails so long as ψ_p is near zero (or 180 deg), and the insensitivity to errors in ψ_f prevails so long as ψ_f is near 180 deg (or zero). Fortunately, a goodly fraction of the data were taken under conditions meeting both of these criteria, tending to strengthen what would otherwise be very low confidence in the results of the analyses.

In view of the data uncertainties and the rather time-consuming calculation procedure (about 10 min per calculated point), the actual analysis procedure did not use an orderly grid of calculated points such as illustrated in Figure 4. Rather, from a first guess at ψ_p and $K_{\ell am}$, subsequent iterative estimates (usually two or three) were made until the result was judged "close enough," and the last estimate was recorded in Table 1. Thus, these estimates could be improved upon by further analysis, if desired.

The second-harmonic pressure amplitudes and phases are not recorded in Table 1; in all cases, they are close to one-third the amplitude of the first-harmonic and 90 deg out of phase. The second-harmonic component is included in the calculations. The effect of the second-harmonic component is to make the pressure wave broad/flat on top and narrow/peaky on the bottom.
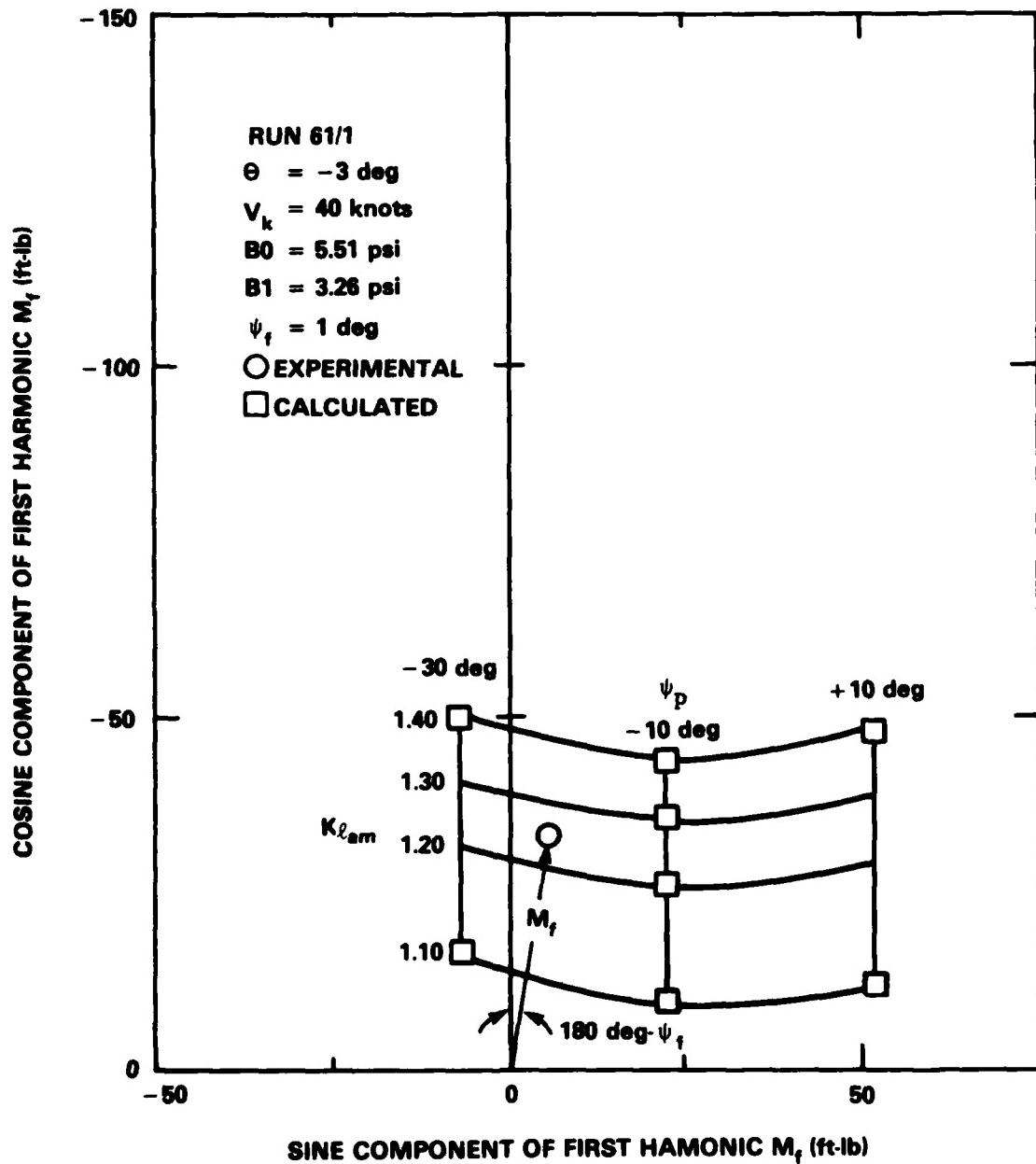
Figure 4 – Effect of Variation in Input Values of $K_{\ell am}$ and ψ_f on Calculated First-Harmonic Components of Roof Flapping Moment

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RESULTS AND DISCUSSION

The results are summarized as plots of λ_1^* versus μ^* in Figure 5. There is a systematic variation with collective blade angle, with the results for $\Theta = 0$ deg falling in reasonably good agreement with the predictions of Reference 1. The results for $\Theta = -3$ deg and $\Theta = -6$ deg, however, fall progressively further above the predictions of Reference 1. This is consistent with the original hypothesis that the first-harmonic inflow term might be greater for rotors with relatively hub-weighted radial load distributions.

Figure 6 shows the calculated blade load per foot at the advancing ($\psi = 90$ deg) and retreating ($\psi = 270$ deg) blade positions for two thrust co-efficients at each of the blade collective angles. At $\Theta = 0$ deg, blade loading tends to increase with increasing radius over most of the blade (as it does for all conventional rotors); at $\Theta = -3$ deg, the blade loading is approximately constant over most of the blade; and at $\Theta = -6$ deg, blade loading decreases rapidly with increasing radius over the outer half radius.

The theory of Reference 1 is a rather heuristic one. It represents the wing-like component of rotor lift, as determined from simple momentum theory, by a horseshoe vortex of span equal to rotor diameter and estimates λ_1 from the normal-to-disk induced velocities of this vortex system on the centerline at the disk leading and trailing edges. If these simple assumptions give a correct estimate for an ordinary rotor (i.e., one with heavily tip-weighted radial load distribution), it might be assumed that a similar estimate using a horseshoe vortex of span less than rotor diameter would be more appropriate for a rotor with a heavily hub-weighted radial load distribution. Alternatively, this speculation can be expressed in the form that such a rotor should behave (for purposes of first-order inflow estimates) like an ordinary rotor at the same thrust but reduced diameter; or like an ordinary rotor of the same diameter but greater thrust coefficient. Such an estimate is achieved by plotting $K\lambda_1^{\ddagger*}$ versus $K\mu^*$, $K>1$, where $\lambda_1^{\ddagger}(\mu^*)$ is taken from Equations (1) through (3).

Such estimates are compared to the results of Figure 5 in Figure 7. Values of $K = 1.25$ and $K = 1.53$ are found to correlate the $\Theta = -3$ deg and $\Theta = -6$ deg data, respectively. (The constants 1.25 and 1.53 were selected purely to fit the data and not from any theoretical considerations.) The degree of data fit

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achieved in this way does tend to support these heuristic arguments and suggests that some further simple theoretical explorations seeking to connect the constant K to the radial load distribution in a quantitative way might be productive.

Because of the substantial uncertainties surrounding the experimental data, it is necessary to question whether any reasonable systematic error could produce the trend exhibited in Figure 7 artificially. The most obvious such possibility, since there was no valid measurement of thrust during the transition tests, is the possibility of a systematic error in the calculated thrust. If the calculation procedure systematically underestimated the thrust at $\Theta = -6$ deg and/or overestimated the thrust at $\Theta = 0$ deg, an artificial difference similar to that displayed in Figure 7 would result. However, to produce the magnitude of difference shown in Figure 7 would require that

$$\left(\frac{\text{Calculated thrust @ } \Theta = 0 \text{ deg}}{\text{Actual thrust @ } \Theta = 0 \text{ deg}} \right) \div \left(\frac{\text{Calculated thrust @ } \Theta = -6 \text{ deg}}{\text{Actual thrust @ } \Theta = -6 \text{ deg}} \right)$$

be equal to $1.53^2 = 2.33$. This is regarded as extremely unlikely.

A second possibility is that the decision to base the analysis on root (hub-center) flapping moment which, in turn, was estimated as 1.25 x (measured flapping moment at 12-percent radius) might produce a systematic error. However, re-analysis of a typical data point at each Θ was performed in terms of the measured 12-percent radius flapping moment (with no additional calibration factor applied). The result was to reduce the estimated value of λ_1^* by about 3 percent in each case. In other words, there was no effect on the trend displayed in Figure 7.

It is concluded that, although significant quantitative errors are possible, the trend displayed in Figure 7 is almost surely real, and rotors with unusually hub-centered radial load distributions do indeed experience unusually severe transition inflow fields.

ACKNOWLEDGMENTS

Figure 5 - Normalized First-Harmonic Inflow versus Normalized Advance Ratio
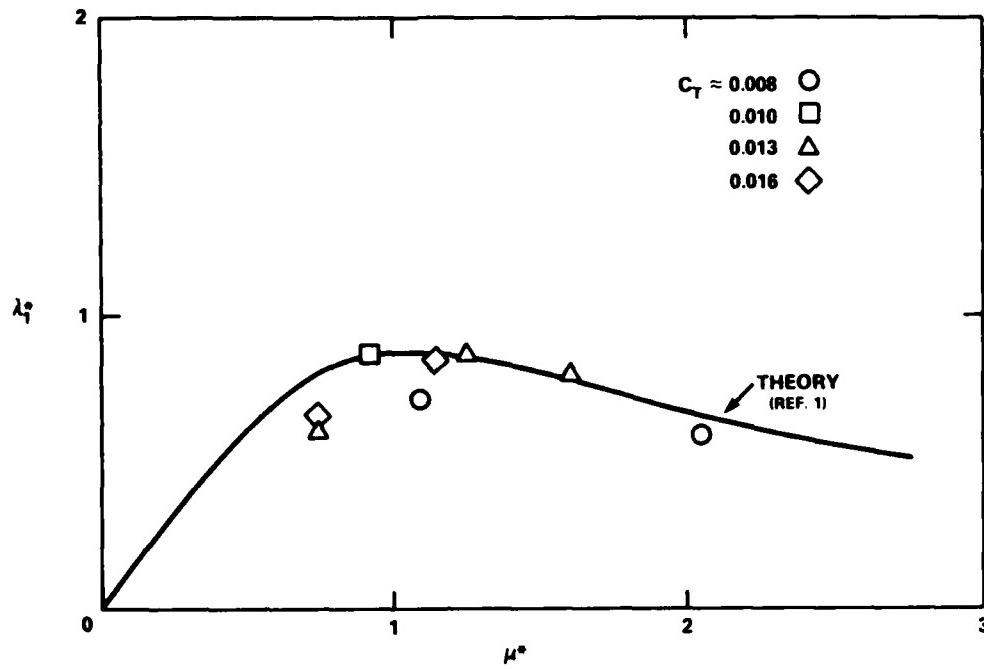

Figure 5a - $\theta = 0$ Degrees
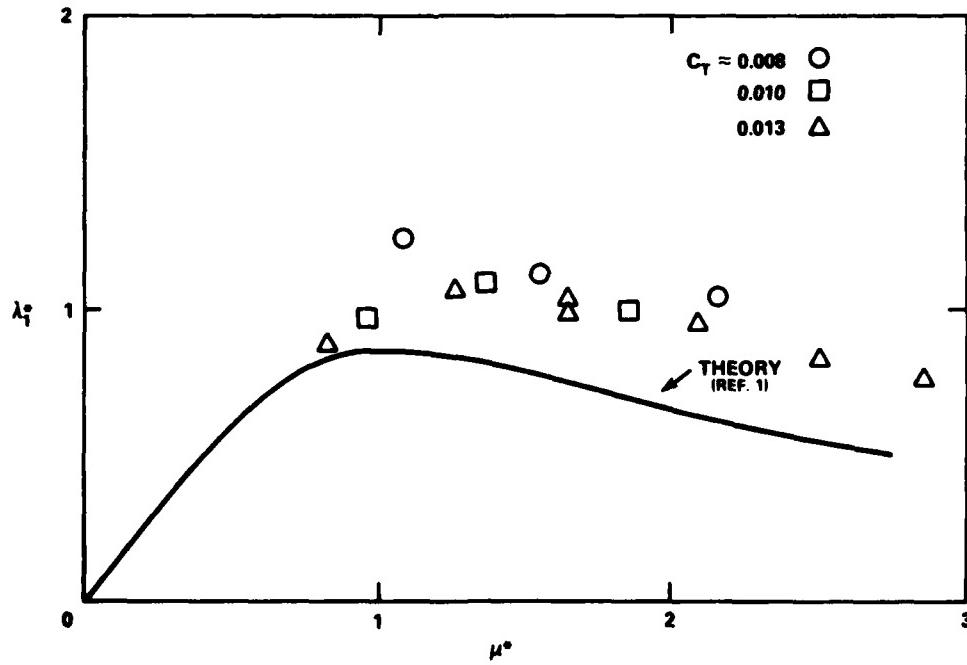
Figure 5b - $\theta = -3$ Degrees

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Figure 5 (Continued)
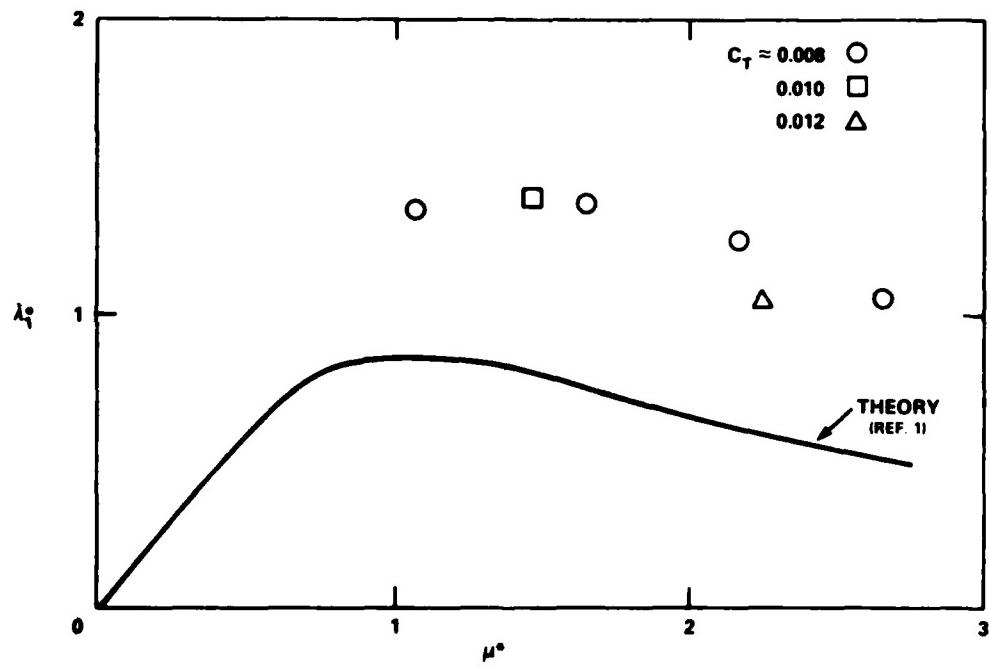
Figure 5c – θ = -6 Degrees

Figure 6 – Calculated Blade Load Distribution on Advancing
and Retreating Blades at a Near-Critical Speed
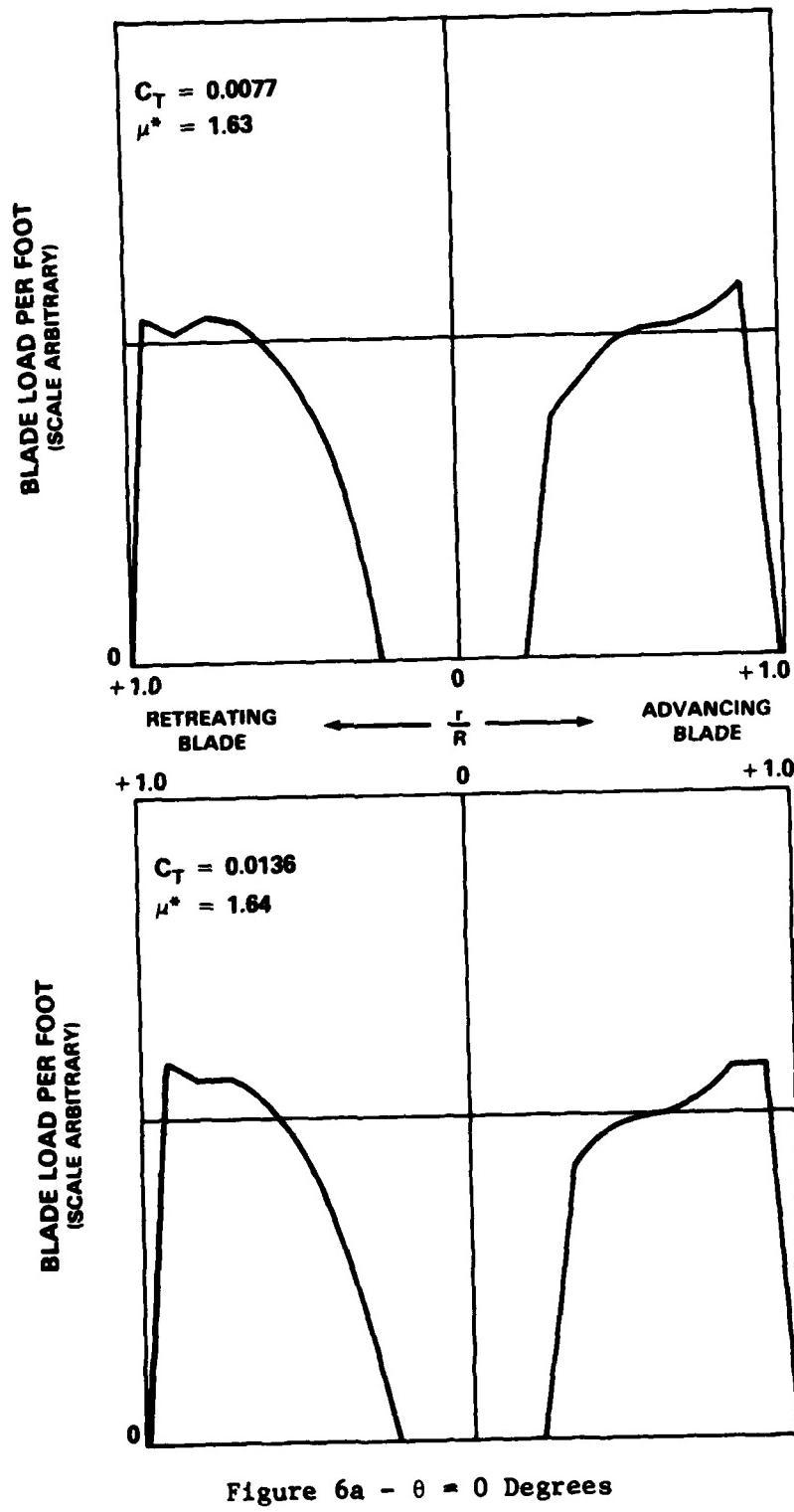
Figure 6a – $\theta = 0$ Degrees

Figure 6 (Continued)

RETREATING
BLADE

$\frac{r}{R}$

ADVANCING
BLADE

$C_T = 0.0079$
$\mu^* = 1.65$

$C_T = 0.0187$
$\mu^* = 1.64$

BLADE LOAD PER FOOT
(SCALE ARBITRARY)
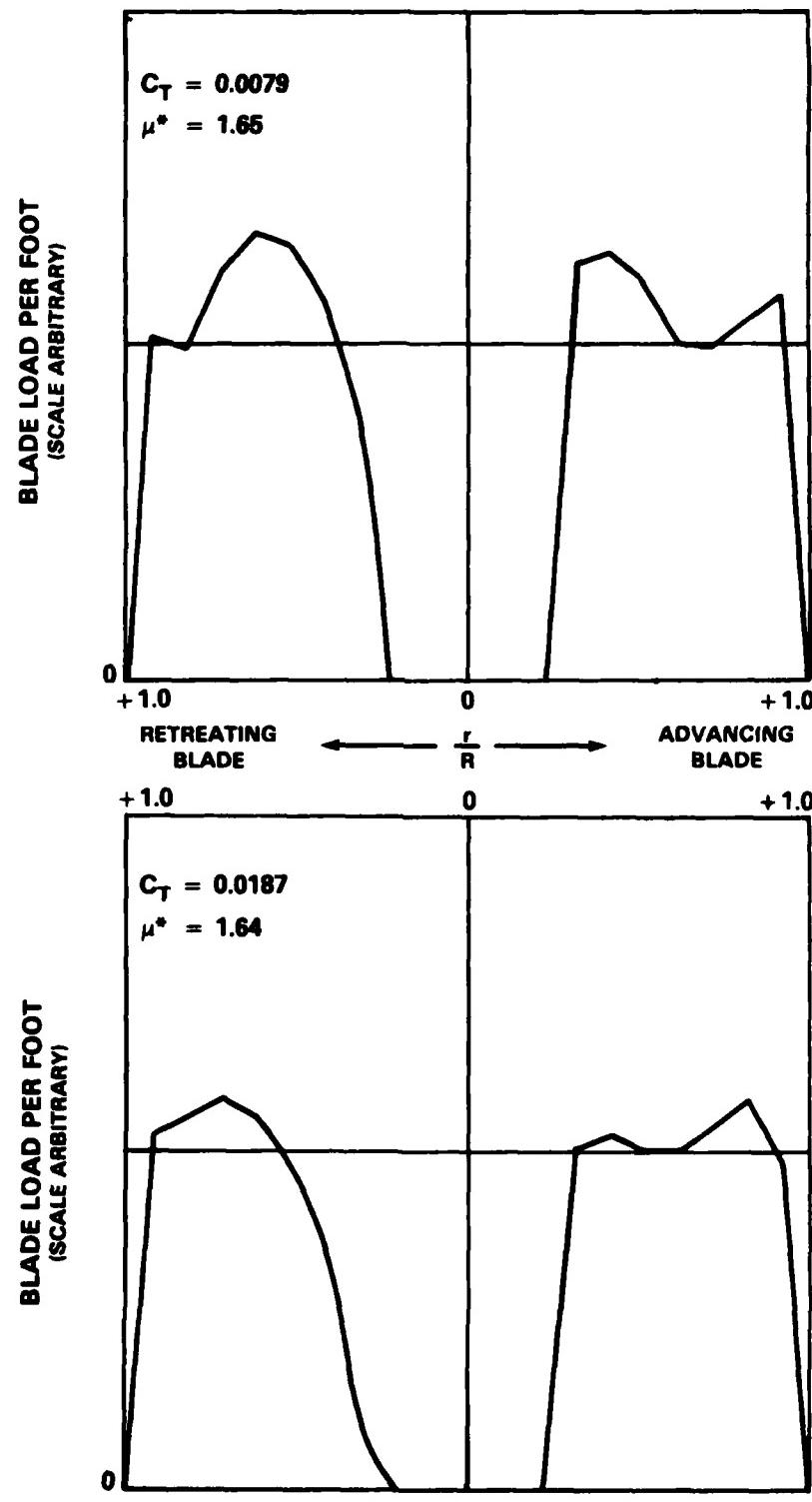
Figure 6b – θ = -3 Degrees

Figure 6 (Continued)

Figure 6c – θ = -6 Degrees

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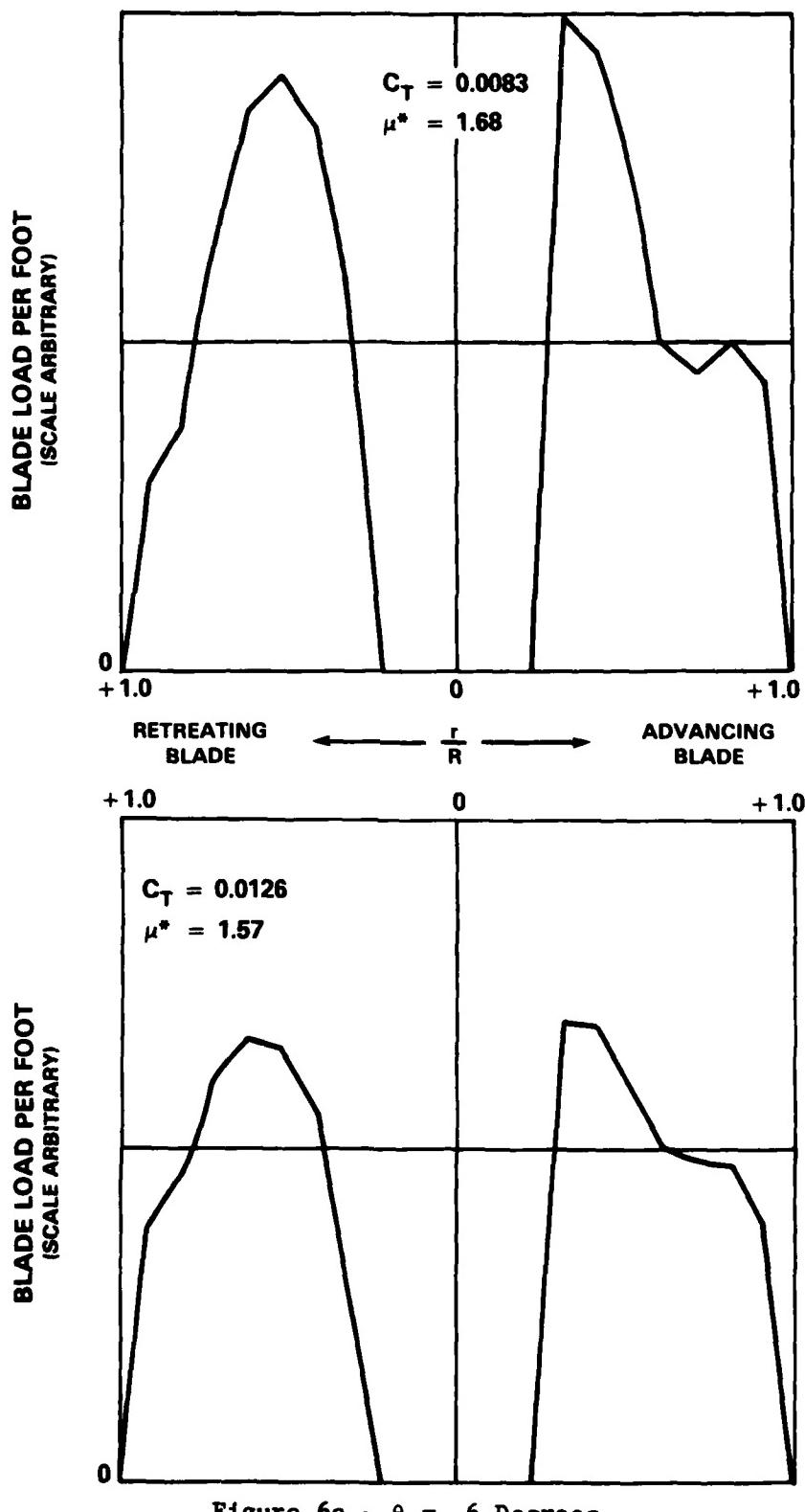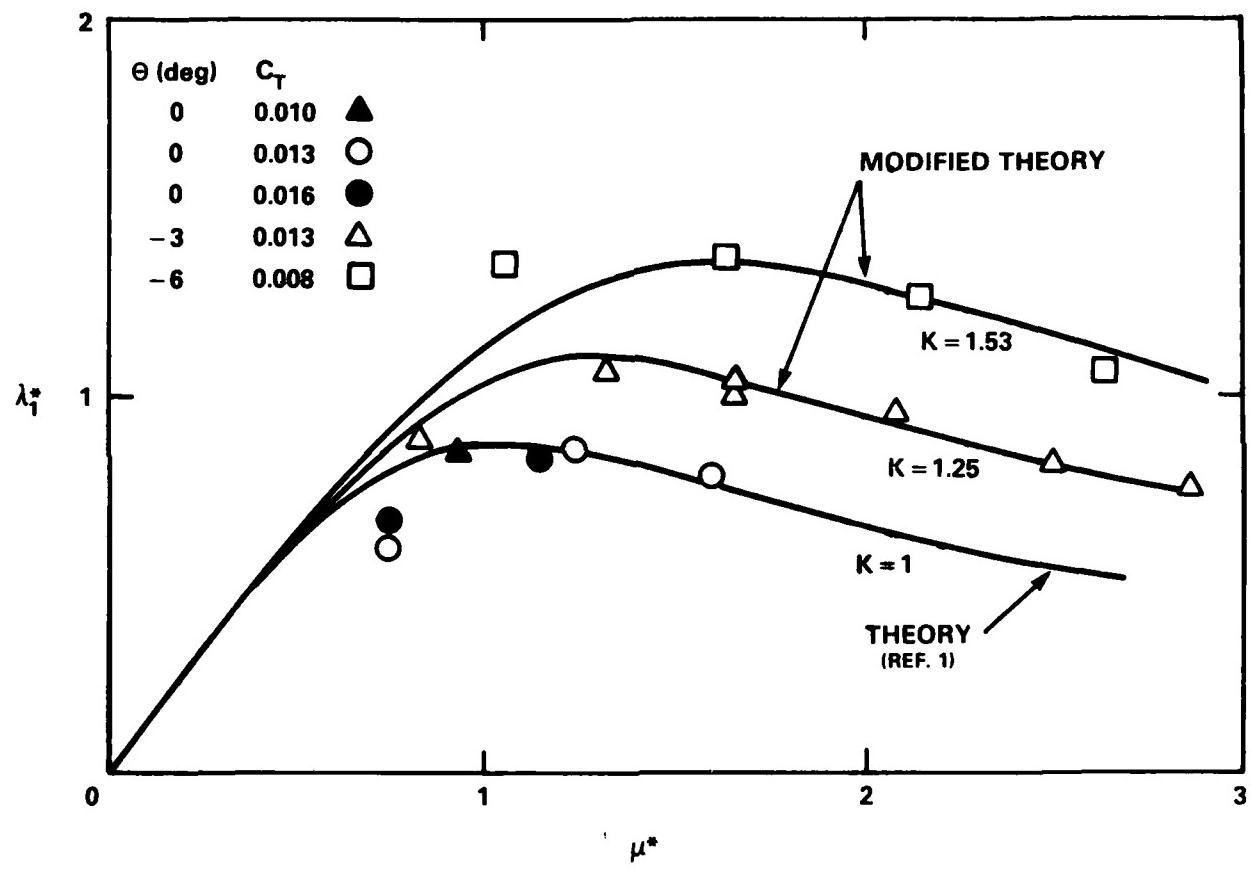
Figure 7 – Normalized First-Harmonic Inflow versus Normalized Advance Ratio
Compared with Heuristically Modified Theory

TABLE 1 - EXPERIMENTAL AND CALCULATED RESULTS

(V_{tip} = 500 ft/sec, α_s = 0 deg)

| RUN/TP	Θ	Experimental							Calculated						
		V_k	$B\emptyset$	B1	ψ_P	M_f	ψ_f	M_{fc}	ψ_P	M_f	ψ_f	M_{fc}	$10^4 C_T$	μ^*	λ_1^*
51/4	0	19.9	1.57	1.04	9	19	154	-17	-5	18	146	-15	76	1.09	0.70
51/5		19.1	2.84	1.80	25	29	126	-17	5	29	128	-18	100	0.91	0.86
51/6		18.3	4.04	2.44	4	13	103	-3	-5	16	103	-4	119	0.80	0.73
51/7		18.3	5.91	3.39	-5	4	327	3	-15	9	63	4	143	0.73	0.60
51/8	-3	20.0	7.82	4.32	4	9	149	-8	-20	11	134	-8	160	0.74	0.64
51/11		30.2	3.67	2.32	10	30	148	-25	-10	34	138	-26	138	1.23	0.86
51/12		29.7	5.07	3.02	11	29	149	-25	-15	32	139	-24	158	1.13	0.83
51/13		39.0	0.86	0.66	-6	26	182	-26	-15	30	153	-25	84	2.04	0.58
51/14		39.5	2.99	1.93	6	29	160	-28	-20	32	149	-28	139	1.60	0.79
53/5		20.5	5.38	3.29	17	14	185	-14	-18	13	199	-13	98	0.97	0.96
53/4		19.8	3.63	2.32	23	24	161	-23	-5	24	164	-23	77	1.08	1.23
53/7		20.0	9.76	5.37	17	31	198	-30	-23	30	182	-30	136	0.82	0.88
54/3		30.0	3.25	2.15	18	28	186	-28	-20	28	195	-27	86	1.55	1.11
54/5		30.0	6.55	3.98	24	41	201	-38	-25	39	188	-39	130	1.26	1.07
54/4		30.0	4.78	2.90	10	32	194	-31	-20	31	185	-31	110	1.37	1.09
55/2		40.0	5.62	3.55	6	40	195	-39	-25	38	184	-38	134	1.65	1.03
61/3		40.1	2.41	1.67	5	28	160	-27	-10	27	173	-27	79	2.16	1.04
61/1		40.0	5.51	3.26	1	34	169	-33	-9	42	145	-34	133	1.65	0.99
61/2		40.5	3.74	2.38	-1	27	155	-25	-10	29	154	-26	108	1.85	0.99
60/5		50.0	4.27	2.53	-13	29	168	-28	-18	33	148	-28	134	2.08	0.95
59/1		60.0	4.74	2.86	-5	23	152	-20	-15	26	142	-20	132	2.50	0.82
58/4		70.0	4.25	2.54	-13	23	130	-15	-23	21	144	-16	133	2.87	0.77

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TABLE 1 (Continued)

RUN/TP	θ	Experimental							Calculated						
		V_k	$B\phi$	$B1$	ψ_p	M_f	ψ_f	M_{fc}	ψ_p	M_f	ψ_f	M_{fc}	$10^4 C_T$	μ^*	λ_1^*
68/4	-6	19.8	7.68	4.42	16	33	211	-28	-10	20	179	-27	83	1.04	1.35
69/3		30.0	5.42	3.33	-1	36	216	-29	-15	32	196	-30	78	1.62	1.39
69/4		30.1	7.47	4.40	20	52	203	-48	-15	45	183	-45	99	1.44	1.40
70/3		40.0	4.93	3.11	1	34	224	-25	-15	27	203	-25	79	2.15	1.27
71/4		49.8	7.00	3.72	-10	44	203	-41	-20	41	184	-41	115	2.22	1.05
71/3		49.8	4.80	2.95	9	29	243	-13	-15	16	214	-13	82	2.63	1.05

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